

A Comparative Analysis of CH₄ Emission Reduction from Municipal Solid Waste (MSW) under Different Scenarios in Kathmandu, Nepal

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Abstract-Currently 516 tonnes of municipal solid waste per day are generated in Kathmandu, Nepal, the majority of which is taken to landfill. This is projected to rise to 745 tons per day by 2025. Landfill is a source of greenhouse gas emissions, most notably methane (CH₄). This study assessed the CH₄ emissions from a landfill site in Kathmandu for five scenarios: S0, S1, S2, S3 and S4. The results showed that CH₄ emissions are extremely high at 15,136 thousand m³ for scenario S0 - "Business as usual". A significant reduction of 53% of CH₄ emissions was achieved with gas capture (S1). Composting (S2) achieved a reduction of 35% reflecting the high organic content of waste that is currently landfilled. Recycling (S3) achieved a reduction of only 10%. Unsurprisingly, the greatest reduction in CH₄ emissions occurred with a combination of gas capture, composting and recycling (S4) with a 73% reduction. The results suggest that gas capture and composting are feasible alternatives. Recycling material should also be considered, as plastics may in the future take up a greater proportion of the waste material over time.

Keywords- Greenhouse gas (GHG), Kathmandu, Methane (CH₄), Municipal solid waste

I. INTRODUCTION

In the Paris Climate Change Conference, 12th December 2015, 196 nations signed an agreement to combat environmental change, specifically to control greenhouse gas (GHG) emissions [1]. Essentially, the Paris Agreement prescribes that GHG emissions should come down to a 'net zero' level by the end of the century [2]. The Paris Agreement sets a long run temperature objective of holding the worldwide normal temperature increment to well below 2 °C, and pursue efforts to limit this to 1.5 °C above pre- industrial levels [3]. It set the worldwide environmental change endeavors on a totally new and dedicated balance: each of the 196 Parties to the UN Framework Convention on Climate Change concurred on a shared objective and way to deal with combatting environmental change and accomplishing worldwide greenhouse neutrality [4]. As part of this there are nationally determined commitments, with each country deciding their own contribution which should be ambitious and progress positively over time.

As indicated by the Intergovernmental Panel on Climate Change IPCC [5] the seven GHGs are: methane (CH₄), carbon dioxide (CO₂), nitrous oxide (N₂O), sulphur hexafluoride (SF₆), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs) and nitrogen trifluoride (NF₃). The three main GHGs, based on their global warming potential are CH₄, CO₂ and N₂O. The primary sources of

GHGs emissions are energy-related production accounting for 65% (mainly from electricity and heat: 28%, transportation: 12%, and manufacturing: 12%), agriculture (14%), land-use change and forestry (12%), and others (6%) [6]. Solid waste contributes 3% of total global GHGs emissions [7].

Solid waste management is of concern, as with an ever increasing global and urbanized population the generation of waste also increasing. This waste has historically been disposed of in open dumps and landfill sites. These destinations produce gas because of the anaerobic disintegration of organic matter. Landfill gas contains roughly equivalent measures of CH₄ (45 to 60%) and CO₂ (40 to 60%) [8]. However, the global warming capability of CH₄ gas is 21 times higher compared to that of CO₂ [6]. Therefore, effective management of CH₄ is important.

The US Environmental Protection Agency [9] has detailed that the landfill site was the biggest source of CH₄ emissions in the United States, representing about 90% of all CH₄ discharges from the waste segment. Landfill sites are also adding to an expansion in GHG discharges in developing countries. For example, in 2000, developing countries were responsible for around 29 % of total GHG emissions, and this is anticipated to increase to 64% by 2030 and 76% by 2050, with landfills being the main reason behind this expansion [10]. In contrast, in developed countries the corresponding GHG outflow is reducing. For instance, the European Union (EU) municipal waste sector diminished from 69x10⁶ tonnes CO₂-e in 1990 to 32x10⁶ tonnes CO₂-e by 2007 and further decreases have been anticipated [11]. This shows decreases in GHG discharges is conceivable.

[12] suggested that developing countries can possibly relieve national emissions by around 5% and in the long term to 10% when coordinated strong waste administration is executed. However, developing countries are facing numerous challenges. First, there is an absence of national statistics on solid waste activity leading to difficulties in computing and large uncertainty in estimating GHG emissions from such activities [13]. Second, difficulties in adopting appropriate approaches. This has led to difficulties in establishing a GHG inventory and subsequent targets for reduction in the solid waste sector.

This study examines the level of solid waste generation and associated GHG emissions and then develops alternative scenarios on ways to reduce these emissions using Kathmandu Metropolitan City (KMC) lying in Kathmandu, Nepal as a developing country case study.

Overview of the Solid Waste Management system in KMC

According to the 2011 Census, the number of inhabitants in KMC was more than 1 million and the normal solid waste generation was 0.3 kg/person/day. The everyday waste generation from various sources was found as 516 ton/day in 2015 [14] with waste collection effectiveness at 86.9% [15]. In 2015, the fundamental source of KMC solid waste was household waste (50%) followed by commercial (44%) and institutional (6%). The largest component of the waste is organic followed by plastics and paper [16].

The waste from households is stored in household bins and unsegregated. Some waste is thrown in the community bins, on roadsides, abandoned spaces and on riverbanks. Most of the waste generated goes directly to the only landfill site called 'Sisdole landfill site', located in Sisdole, which is around 28 km away from Kathmandu city. The landfill site was established with the assistance of JICA

(Japan International Cooperation Agency) in 2005 with a project life of 3 years but, as there is no alternative waste disposal site, the waste from Kathmandu valley is still being dumped there [17].

KMC is the focal organization accountable for handling the waste generated in KMC. A total of 1,320 staff are engaged to manage the solid waste[14] .These staff are spread across 32 ward offices, each has tractors or tippers and 20-30 sweepers, amounting to 927 street sweepers in total. Some private sector and Non-Government Organization (NGOs) also have sweepers to clean the streets. Figure shows a detail schematic representation of the municipal solid waste flow in KMC.

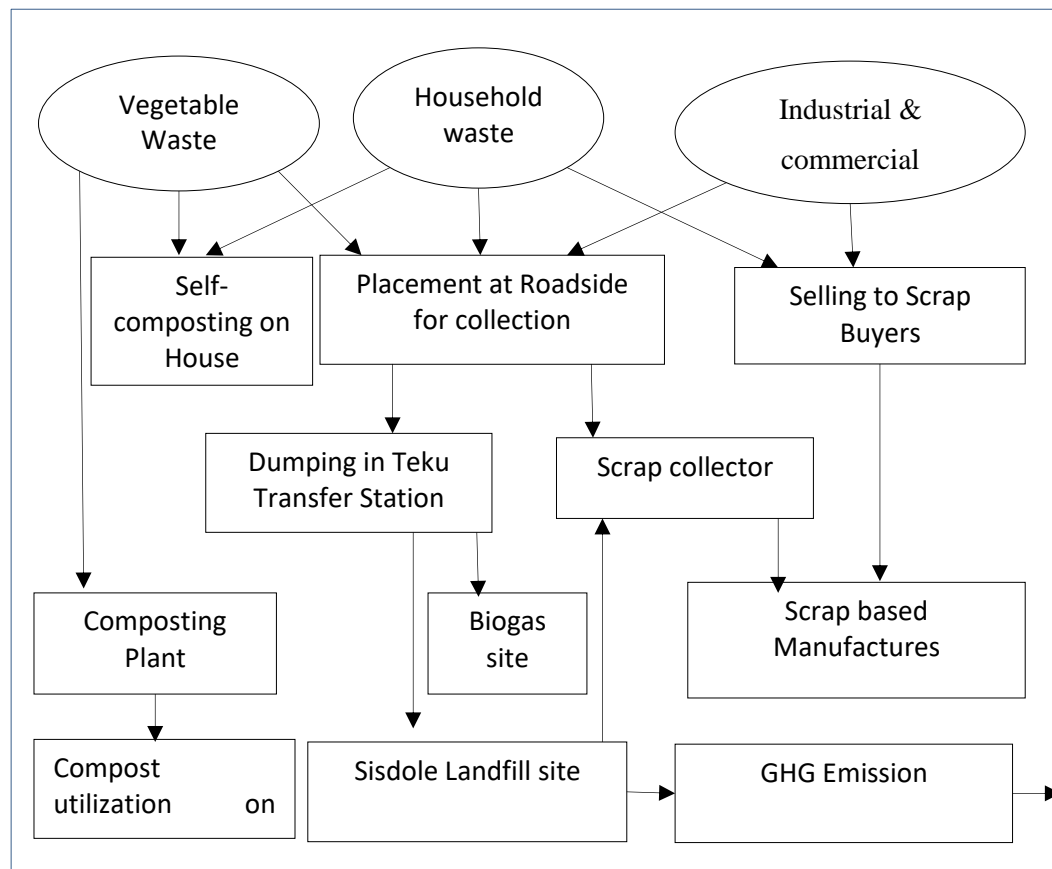


Figure 1: Municipal solid waste flow of Kathmandu Metropolitan city(develop by Author)

II. RESEARCH METHODOLOGY

Study area

The study area Kathmandu Metropolitan City (85° 20' East and 27° 42' north) lies in Kathmandu Valley of Nepal. It covers an area of 50.67 km². The elevation of Kathmandu lies 1,350 meters above mean sea level [18]. The Kathmandu valley has a mild climate most of the year with summer temperatures ranging from 19-27°C, and winter temperatures ranging from 2-20°C. Total annual rainfall in the area is 1,505 mm with around 80% rain occurs during rainy season (June to August) [19]. The Kathmandu City is divided into 5 major sectors and 32 wards as the decentralized units as shown in **Error! Reference source not found.**

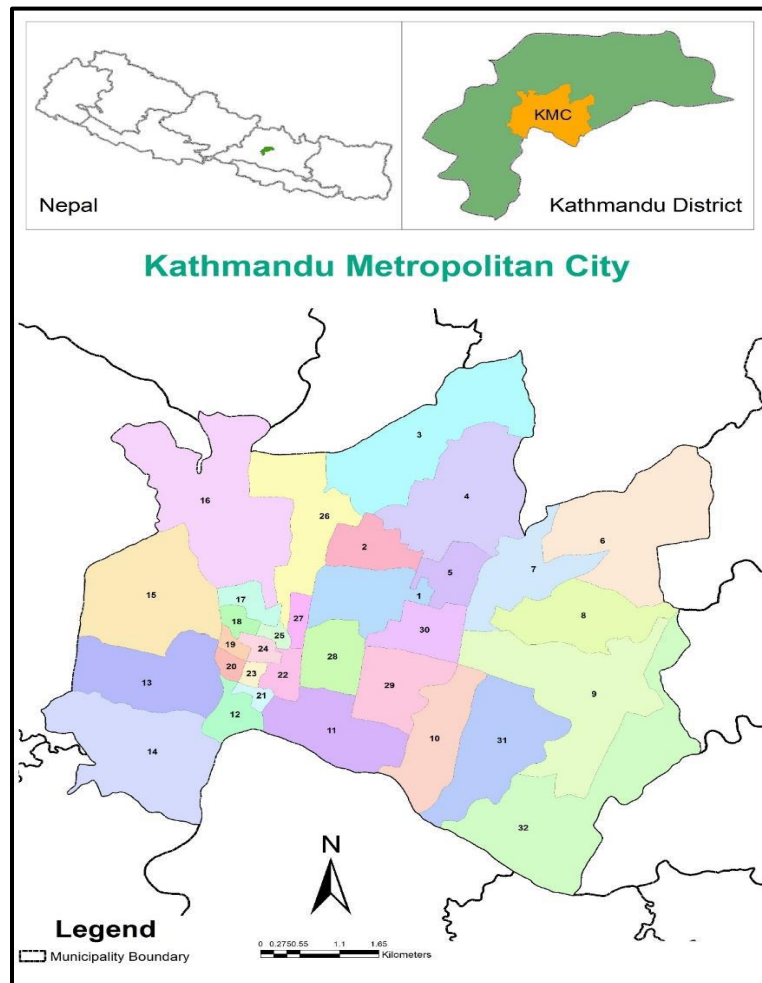


Figure 2: shows the location of the study area, Kathmandu, Nepal [20]

In the last 20 years the population of the city has grown at an annual growth rate of 4.8% from 0.67 million in 2001 to 1.0 million in 2011[21] . Due to rapid population growth and urbanization the quantity of waste generated in Kathmandu city is increasing rapidly, demanding special attention for proper Solid Waste Management (SWM).

Figure 3 shows that there is a strong linear relationship between waste generation and population with coefficient of regression $R^2 = 0.99$. Based on this regression waste quantity by 2025 is predicted to be 271,965 tonnes.

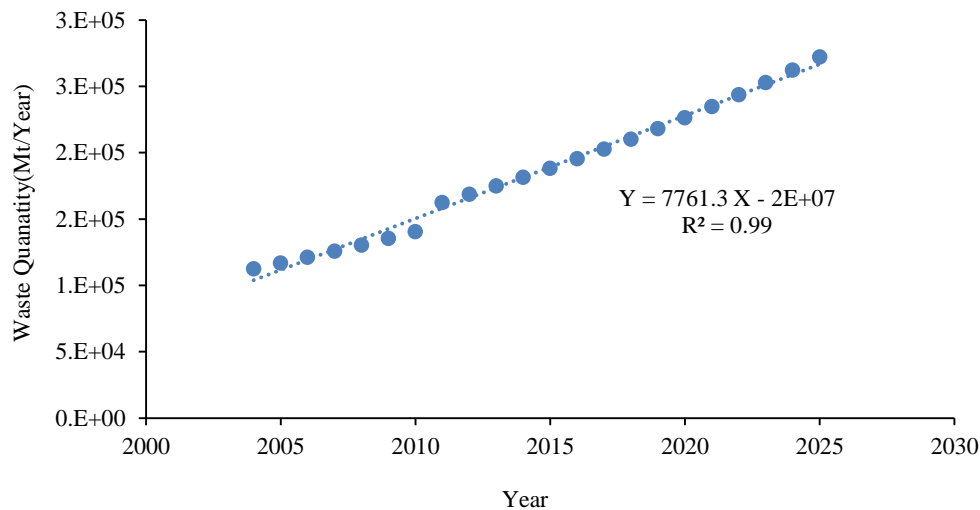


Figure 3: Yearly waste generation trend in Kathmandu city, Nepal [22]

Framework for Research Methodology

The framework for the research methodology is shown in Figure 4. In Phase 1 Life Cycle Assessment (LCA) is proposed as the key research strategy. The principles and framework for LCA include defining the goals and scope, Life Cycle Inventory (LCI) analysis, Life Cycle Impact Analysis (LCIA) and Life Cycle Interpretation [23]. In view of the structure of LCA, the objective and extent of the investigation will be re-imagined. Likewise, predictive scenarios will be structured, and discharge stock techniques will be chosen. Most of the calculations will be made based on Inventory Analysis, as the purpose of the study will be to analyse potential environmental benefits through alternative scenarios. The focus of the scenarios is on the current situation in Kathmandu and potential future waste treatment facilities which fit with the waste characteristics of Kathmandu targeting less energy consumption, low emissions whilst being cost effective with maximum social benefits acceptable to society.

Phase 2 involves emission accounting and evaluates CH₄ discharges by utilizing two numerical models: IPCC default; and first order decay (FOD) model [24]. The results for every situation are then evaluated and compared to determine the best MSW management for Kathmandu in regards to reducing GHG emissions.

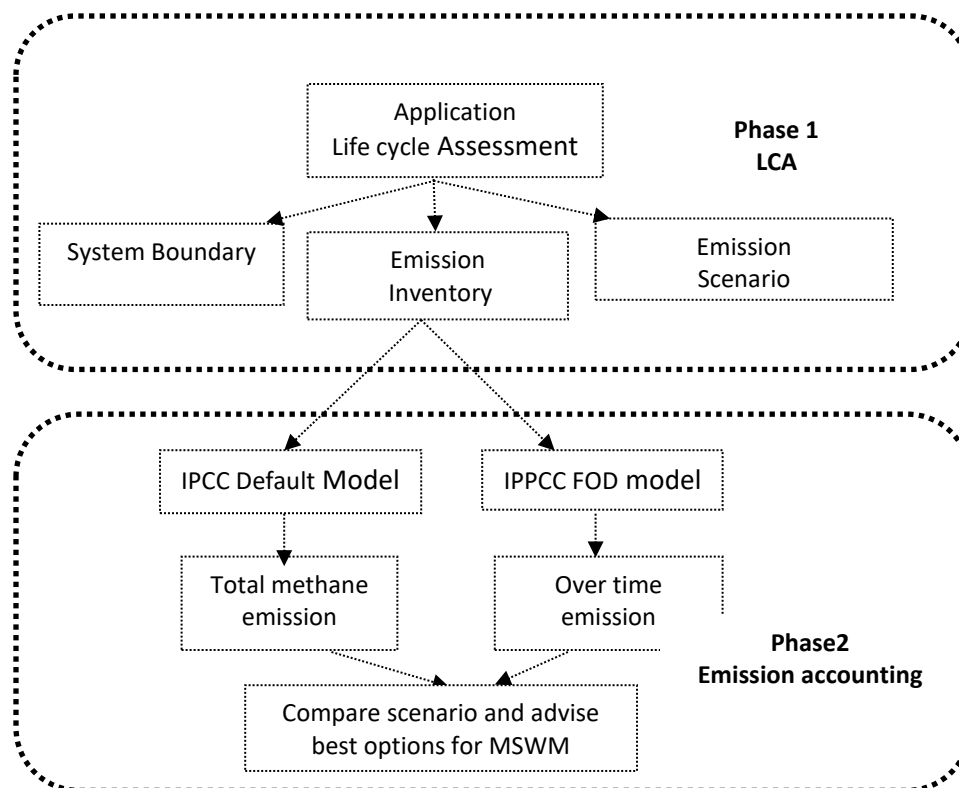


Figure 4: framework for Research Methodology

Scenario development in LCA

In this section, scenarios are defined and created for analysis in LCA. The scenario design in this research investigates the potential decrease of the environmental impacts associated with a potential decrease in CH₄ emissions as a result of the alternative scenarios identified.

MSW in KMC is collected waste without segregation at the source, mixed with other waste and conveyed to Sisdole landfill site. The existing Sisdole landfill site, however, is overloaded. Accepted Government policy is focused on improving MSW management systems, especially, with the rate of increase in food waste and recyclable components in MSW. This has led to some segregation of food waste and inorganic waste at source to be treated by composting and recycling, rather than landfill.

The five scenarios proposed in this study with system boundaries are illustrated in Table I. The baseline scenario (S0) represents the existing MSW management system which is the current status of MSW undertaken by KMC, and the subsequent scenarios reflect alternative options, including composting and recycling, and also gas capture from the existing landfill site.

Table I: Description of scenarios used in this study

Scenarios	Explanation of Scenarios Used
S0	Current 'Business as usual' (Landfilling of 87% of collected MSW)
S1	Upgrade to landfill gas capture (70% Methane recovery)
S2	Composting 50% of organic waste
S3	Recycling 25% of recyclable materials
S4	Integration of gas capture, recycling and composting

Current 'Business as usual' (S0)

The business as usual scenario includes the collection, transport and landfilling of MSW. This is the current status of MSW undertaken by KMC. A very small fraction of the waste is recovered as recycled materials, but this is not considered here. According to the environmental audit report [14], MSW is not isolated at the source and roughly 448 tons of waste for each day are discarded in the Sisdoile Landfill site with no further treatment. Sisdoile Landfill site is structured as a semi anaerobic landfill site, without a recuperation framework or a LFG catch system. Data on the solid waste composition of Kathmandu Metropolitan City during the years 2003, 2005, 2009, 2013 and 2015 are shown in Table II [15],[16],[14]). The waste composition data of the year 2015 is considered for the calculation in this study work.

Table II: The physical composition of solid waste of KMC (%)

Year	Organic Waste	Plastics	Paper	Glass	Metals	Textiles	Rubbers	Construction and demolition	Others
2003	70.00	9.50	8.50	2.50	-	3.00	-	4.50	2.00
2005	69.00	9.00	9.00	3.00	1.00	3.00	1.00	2.00	3.00
2009	63.00	10.00	9.50	6.00	0.50	2.00	1.00	5.00	3.00
2013	73.22	11.43	6.89	2.10	1.06	1.61	0.62	-	3.07
2015	63.22	10.80	9.02	5.42	0.42	2.30	1.20	4.50	3.12

Upgrade of Landfill gas capture (S1)

The landfill gas capture scenario is the same as S0 but assumes 70% of CH₄ gas is gathered. Landfill gas (LFG) is naturally produced by the decomposition of organic materials (also known as biomass) and increasing moisture content can accelerate the waste decay process. The rate of LFG production thus also increases with moisture content, peaking at waste moisture contents of 60 to 78% [25]. Sisdoile landfill waste has an average moisture content of about 35.3 %, with a high volume of food and vegetable waste having a higher moisture content [26]. After waste placement, rainfall, surface water and groundwater infiltration, together with the products of waste breakdown, can contribute additional moisture. Based on these existing conditions, and observations of existing vent pipe placements to allow methane gas to escape alongside discussion with KMC staff, this scenario assumes that the introduction of a gas

capture system will be effective at gathering 70% of the gas produced ($R=0.7$). Other parameters in the scenario are the same as S0. The estimation of the model parameters for scenario S1 are shown in Table 3.

Composting of organic waste (S2)

In this scenario the composting of 50% of organic waste from 86.9% of the landfilled waste is isolated, gathered and composted with the remaining waste sent to landfill. This figure is based upon discussions with KMC staff on the feasibility of the process. In this scenario using input data, 50% of organic waste is identical to 51,743 tons of the 103,486 tons of organic waste which can be treated as compost. The adjustment in the waste amount and level of the waste composition for the input scenario S2 are shown in Table 3.

Recycling prior to landfill (S3)

Based on the study of Kathmandu solid waste management Bank [15], 25 % of household waste and a much higher proportion of institutional and commercial waste could be either reused or recycled. This is excluding organic waste. This scenario therefore assumes that 25% of the MSW from the amount of buried MSW, including paper, metals, glass, plastic, construction and demolition waste, and textiles is separated at the source and recycled with the remaining waste sent to landfill. It is assumed that a similar measure of MSW, with a similar composition as in S0 is covered. The adjustment in the waste amount and level of the waste composition for the input scenario S3 are shown in Table 3.

Integration of capture, recycling and composting (S4)

Firstly, 50% of organic waste from landfilled MSW will be gathered and treated by fertilizing the soil to make compost in S2. Moreover, recyclable materials, for example, paper, metals, glass, plastic, wood and material will be recycled at a 25 % rate in the material recycling facility. The remaining waste is sent to the landfill. Lastly, in assumption S0, 70% of CH₄ emissions will be collected and recovered. The same amount of MSW, with the same composition in S0, is delivered and treated at the landfill site.

System boundaries

The practical unit in this examination is the aggregate sum of waste produced in KMC in a year, i.e. household, commercial, and institutional. This amounts to 163,666 tons in terms of solid waste collected. The functional system boundaries selected for this LCA only includes the direct emission from the waste after landfill where waste was characterized as the minute when material stops to have value.

In this examination, figure 5 presents the key points for each scenario for the MSW management system in Kathmandu. The upstream limit begins with MSW being dumped in the landfill site. The procedure of collection and transport is excluded in the framework stream for all scenarios. It is on the grounds that it is hard to recognize and isolate the GHG outflows produced from the collection and the transportation that might be conveyed to either landfilling or other treatment destinations.

Unit procedures incorporated into the emissions scenarios are: (1) foundation of landfill, for example, establishment of LFG catch framework; (2) integrated composting to landfill; (3) coordinated recycling to landfill. Deciding the unit forms and isolating each and every unit procedure from the principle framework help to assess their environmental impacts inside the framework. Any change will prompt changes in the first framework

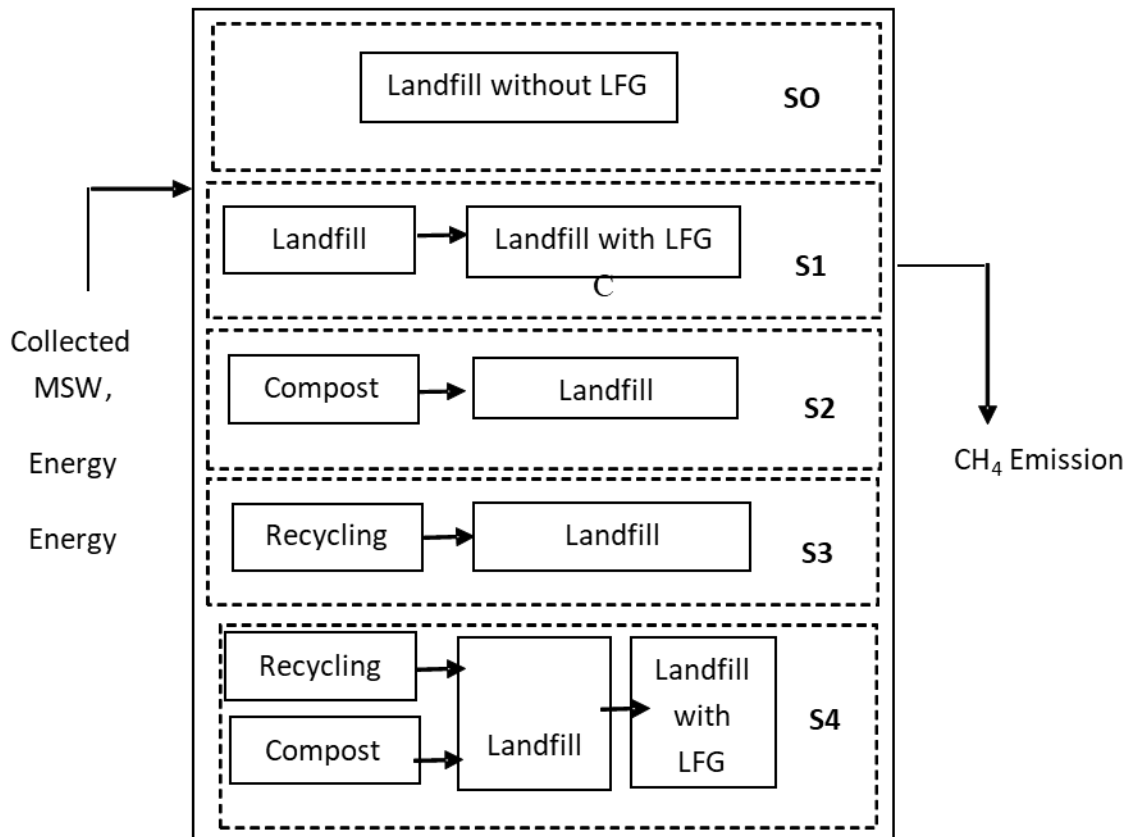


Figure 5: System boundary

IPCC Model / IPCC default method

The IPCC suggests two methods for calculating methane emissions from landfill sites, the default method and the first order decay method. The least complex one for the estimation of methane outflows from landfills depends on a mass equalization approach. This is the default methodology (DM). DM is fundamentally an empirical model. Various empirical constants have been considered while building up the DM. The empirical constants vary according to the composition of waste, management of the landfill site and depth of landfill. The method assumes all emissions of methane occur in the same year as the waste is deposited at the landfill site [27]. Even though this is not the case, the IPCC state that the DM gives a sensible annual estimate of actual emissions and this has been broadly utilized in the circumstances where point by point information is not available [13]. The Default model requires the MSW amount and composition that is sent to the landfill site and data on the current activity of the site. As per IPCC Guidelines, the equation for determining GHG emission from solid waste landfills is as per the following [28]

$$\text{Methane Emission- } ECH_4 (\text{Gg/yr}) = (\text{MSWT} \times \text{MSWF} \times \text{MCF} \times \text{DOC} \times \text{DOCF} \times F \times (16/12 - R) \times (1 - OX)) \quad \text{Eq 1}$$

Where: 1 Gg/yr: 1000 Mg/yr

Where: ECH_4 = Methane emission from landfills. MSWT = Total MSW generated (Gg/year), MSWF = Percentage of urban waste actually land filled; MCF = methane correction factor (fraction), DOC = degradable organic carbon (fraction) (kg C/ kg MSW) DOCF:

fraction DOC dissimilated, F = fraction of CH_4 in landfill gas (IPCC default is 0.5), $16/12$ = conversion of C to CH_4 , R = recovered CH_4 (Gg/year), OX = oxidation factor

Modified FOD method

In the First Order Decay (FOD) model methane generation from landfill is a function of time mirroring the actual time that it takes material to decay. The FOD model requires information on current waste amounts, composition and disposal practices extending over decades [27]. At present due to lack of data, this method cannot be used for estimation of methane emission. Therefore, a modified model has been used. The modified model is the NV Afvalzorg Multiphase Landfill Gas Generation and Recovery Model, which is a first order decay model based on IPCC mathematics and default parameters and the model estimates methane generation, recovery and emission on individual landfills for which limited data on waste composition are available [29]. Various sorts of waste contain different fractions of organic matter that degrade at various rates. The advantage of the NV Afvalzorg Multiphase model is that the typical waste composition can be taken into account [30]. The estimation approach IPCC 2006 rules for solid waste disposal site was followed. Furthermore IPCC default values were adopted as much as possible [24]. The formula used in this model for calculating methane generation (G) is as follows. For this model the time horizon is 100 Years.

$$G = WLo [F(f)(K(f)e^{-K(f)(t-t(1))}) + F(s)(K(s)e^{-K(s)(t-t(1))})] \quad \text{Eq 2}$$

Where:

G = Methane generation (million cubic meters per year), W = Waste disposed of (Tonnes), Lo = Methane yield potential (cubic meter per tonne of waste), T = Time after waste placement (year), $T1$ = lag time (between placement and start of gas generation), $K(f)$ = First-order decay rate constant for rapidly decomposing waste, $K(S)$ = First-order decay rate constant for slowly decomposing waste, $F(f)$ = Fraction of rapidly decomposing waste, (S) = Fraction of slowly decomposing waste

Information parameters for models

Municipal Solid Waste Tonnage (MSWT): Based on the existing MSW management practices in Kathmandu, along with its landfill features, climatic condition, the wet tropical climate, the default parameters for all factors used in the models is presented in detail in Table III. Total municipal solid waste (MSW) generated Ga/year (MSWT) was calculated from population (in thousand persons) multiplied by annual MSW generation rate. According to the environmental audit report [14] total MSW is equal to 163,666 tonnes of solid waste and therefore this is the amount that was applied to the model.

Methane correction factor (MCF): the value of the methane correction factor (MCF) reflects the status of landfill management of the site. To accommodate different types of landfill sites, the IPCC recommends default MCF values, ranging from 0.4 to 1. This corresponds to a range of unmanaged to well-managed landfill sites. In Sisdoile Landfill site, the burial areas of MSW is well managed with a top cover of soil, supposing that the value of MCF is 1, this is applied for all scenarios.

Degradable organic carbon (fraction): DOC substance is fundamental in processing methane generation. It relies upon the composition of waste and changes from scenario to scenario. The organic fraction of each type of organic waste is considered as having different decay rates [31] shown in the following equation.

$$\text{DOC} = (0.4 * A) + (0.17 * B) + (0.15 * C) + (0.3 * D) \quad \text{Eq 3}$$

Where, DOC is degradable organic carbon, A: fraction of paper and textiles; B: fraction of garden waste and park waste; C: fraction of food wastes and D: fraction of MSW as wood or straw.

Applying measurable information on waste composition in the KMC MSW, the level of DOC in MSW is 14.1%. This figure is for scenario S0 and S1. In contrast with S0 and S1, the estimations of DOC applied to the remainder of the scenarios are 13.7% for S2, 14.1% for S3 and 13.69% for S4 (Table 3).

Fraction DOC dissimilated: This is the DOCF that is changed over to LFG. The theoretical model is linked to the temperature in the anaerobic zone of a landfill site. The model is depicted as $0.014T + 0.28$, where T=temperature in °C [27]. It is expected that temperature stays steady at 35°C in the anaerobic zone of the landfill. This results in a figure of 0.77.

Fraction of methane (F) in LFG (default is 0.5): The division of methane in LFG is expected to be 0.5, and is the figure used here.

R (Recovered methane) (Gg/year): Recovery of LFG does not yet take place in Nepal. For scenario S1 and S4 it is assumed that if a gas capture system is introduced it would be effective at collecting 70% of the gas produced (R0.7). Additionally, using a landfill top cover of soil the default parameter for the oxidation factor will be 0.1 [13].

Table III: Input parameters used in calculation for scenarios

Input Parameters	MCF*	D0C	DOCF*	F*	R	OX*
S0		14.11%			-	
S1		14.11%			0.7	
S2	1	13.70%	0.77	0.5	-	0.1
S3		14.10%			-	
S4		13.69%			0.7	

*All scenarios Average value

MSW is classified into rapidly, moderately and slowly degradable organics. Rapidly biodegradable organics (food waste) starts decomposing a few days after waste is placed in the landfill and take up to five years to complete decomposition. Moderately degradable organics (garden and park waste, leaves, grass trimmings) start the degradation process after a few months and finish after seven to ten years of burial. Paper, textile, leather, rubber, and wood are slow to biodegrade and begin decomposing about five years

after they are buried in a landfill site and might take up to 50 years to complete the process [32]. In this calculation data from 2005 to 2018 on annual deposited waste in Sisdoile landfill site from KMC was used.

In this study, the consideration of value k was dependent on the climate condition at the Sisdoile Landfill site, the waste component and reference of IPCC default k values. Sisdoile landfill site is located in near Kathmandu valley under a warm humid tropical climate with precipitation being around 1505 mm per year and the annual average temperature being about 19-27°C. Therefore, default values of k and the corresponding half-lives have been taken from 2006 IPCC Guidelines for a tropical climate zone with mean annual temperature over 20°C and mean annual precipitation over 1,000 mm. According to the equation $K=3.2 \times 10^{-5} (R) + 0.01$ of US [9]) where R is the annual precipitation, the calculated value of k is 0.06 and corresponding $t_{1/2}$ is 10 years.

III. RESULTS AND DISCUSSION

Waste composition under different scenario in KMC

One significant aspect of solid waste in KMC from a management perspective is the huge volume of organic materials in the solid waste stream. The remainder of the waste contains glass, metal, rubber and other materials. Organic waste accounts for 60–70% of all solid waste and the level of this waste which is biodegradable is strikingly high. The official figures of KMC for the year 2015 demonstrate that practically 63.22% (by weight) of the waste produced in KMC is organic followed by plastic and paper. A similar amount of waste with an unchanged composition is used in the computation for this study. Thus, the waste creation information for the year 2015 is used in scenario Current 'Business as usual' (S0). It remains the same for the gas recovery scenario (S1). For Scenarios S2, S3, and S4, the expansion in recycling and composting of MSW decreases the aggregate sum of solid waste sent to the landfill site. This gives rise to new percentages for the composition of waste (Table IV).

For S0 and S1 scenarios, the MSW in Kathmandu contains a high extent of organic waste, representing over half (63.23%) of the landfilled waste. Similar levels are seen in scenario S3 with 69.04% of organic waste. On the other hand, scenarios S2 and S4 have a lower extent of organic waste (46.23% and 52.72% individually), they additionally have the highest level (percentage) of gradually degrading waste (paper, material, plastic, glass and metal). This determines the varying levels of CH_4 outflows and also the age of the landfill in every scenarios.

Table IV: Solid Waste material composition stream of scenarios

Solid Waste composition (%) in different scenarios										
scenarios	Amount of Waste (tonnes)									Demolition Waste
		Organic	Plastic	Paper	Glass	Metal	Textiles	Rubber	Others	
S0 & S1	163,666	63.23	10.80	9.02	5.42	0.42	2.30	1.20	4.50	3.11
S2	111,923	46.23	15.79	13.19	7.93	0.61	3.36	1.75	6.58	4.55
S3	149,894	69.04	8.84	7.39	4.44	0.34	1.88	0.98	3.69	3.40
S4	98,151	52.72	13.51	11.28	6.78	0.53	2.88	1.50	5.63	5.19

For Scenarios S2, S3 and S4 there will be a change in the aggregate sum of waste sent to landfill with the expansion of composting in S2, in recycling for S3 and both composting and recycling in S4. Figure 6 illustrates the tonnage composition for each scenario.

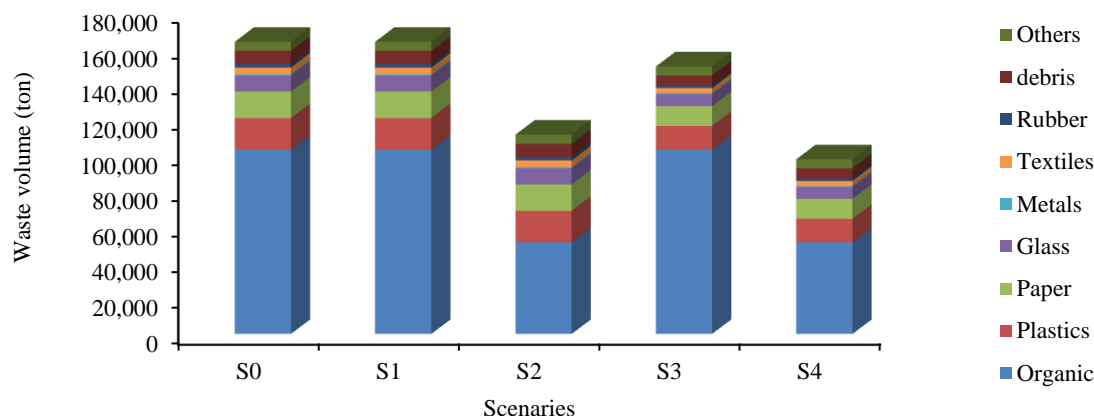


Figure 6: Waste fraction volume follow stream in different sceneries

Potential methane (CH₄) emissions

The potential outflows of CH₄ from the Sisdole Landfill site using the IPCC default model varies between the five scenarios as shown in Table V. Scenario S0 (Business as usual) demonstrates that the aggregate sum of CH₄ discharged is 15,136 m³ while the scenario S4 (Landfill, recycle and compost) reduces CH₄ emissions by 11,049 m³ to 4,114 m³. In the event that a gas recuperation framework is introduced (S1), it would by itself lessen CH₄ outflows by 8,022 m³ down to 7,069 m³. The next best alternative is S2 (Composting) which reduces the CH₄ outflows by 5,298 m³ to 9,882 m³. S3 (Recycling) is the least effective option reducing CH₄ emissions by only 1,514 m³ to 13,663 m³.

Table V: The Potential emissions of various scenario utilizing IPCC default model

Scenarios	Amount of waste (tonnes)	CH ₄ emissions (m ³)	Emission Reduction m ³
S0 (Business As Usual)	163,666	15,136	-
S1 (Gas Capture)	163,666	7,069	8,022
S2 (Landfill/Compost)	111,923	9,882	5,298
S3 (Landfill/Recycle)	149,894	13,663	1,514
S4 (Landfill/Recycle & Compost)	98,151	4,114	11,049

Figure 7 shows the emission reduction for each scenario in percentage terms. All scenarios reduce CH₄ emissions, with minimal advantage from recycling reflecting the relatively limited amount of recyclable material that is actually landfilled. Composting leads to a much greater reduction in emissions, related to the greater amount of organic material that is currently collected and landfilled. This also has implications for gas capture. The greatest reduction understandably is with the integration of all three scenarios.

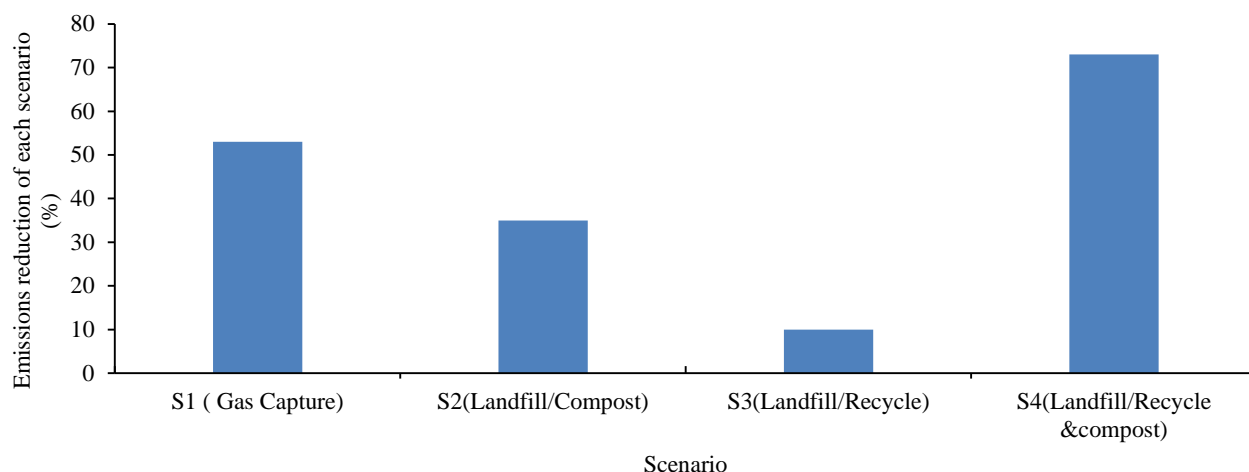


Figure 7: The total emissions (%) reduction of each scenario

Volume Disposal of landfill Waste

In the S0 (Business As Usual) scenario of Figure 8, the volume of waste coming to the landfill site is 163,666 tons per year, which takes up a large volume in the landfill as compared to scenario 2 and 4. Waste coming to landfill indicates that its life will decrease faster due to the huge volume of the waste. The volume of the waste scenario 0 and 1 is the same at 163,666 tonnes per year respectively. The only difference is that in scenario 1 the waste is used to generate gas through the 70% gas capture system. In scenario S0, there is no gas capture and mixed waste is directly disposed as usual. In scenario 2, the volume of the waste decreases to 111,923 tonnes per year due to more recycling of recyclable materials and recovery of organic materials. In scenario 4 Furthermore, the volume of landfill waste decreases to 98,151 tonnes in scenario 4. This is due to 50% of compost recycling, 70% of methane recovery at the landfill and 25% inorganic waste recycling as integration method.

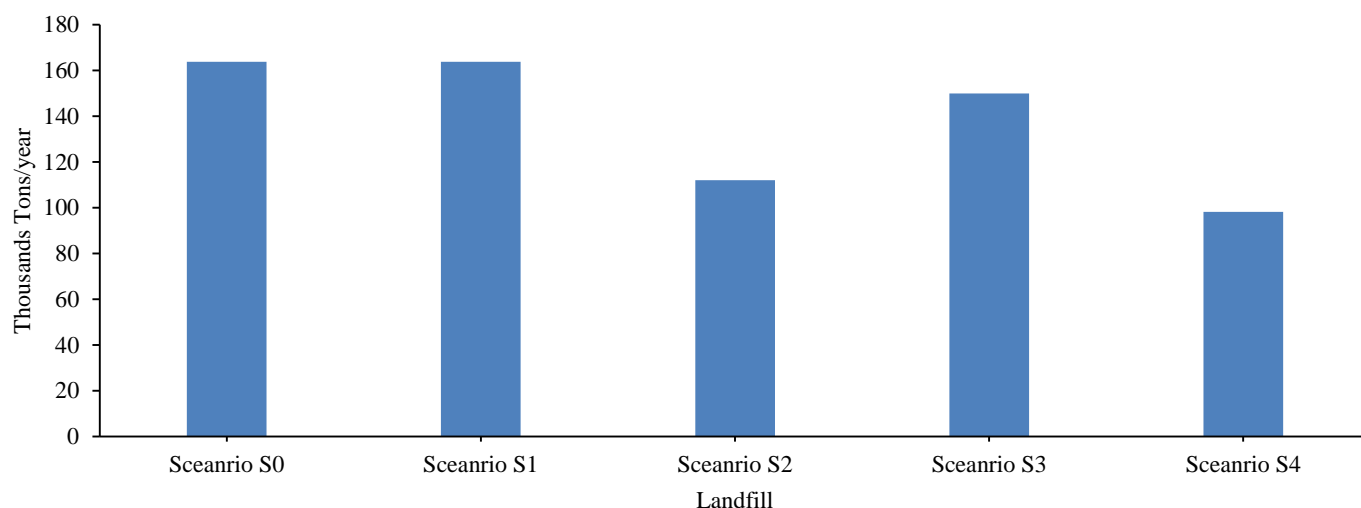


Figure 8: Final disposal of waste volume in different scenarios

Difference in methane (CH₄) production over time

The methane emission values from solid waste landfill estimated for 2005 to 2018 using the default method and NV Afvalzorg model are shown in Figure 9. The assumption made in DM is that the potential methane is emitted in the same year that waste is deposited. This may not be realistic. The values used in the FOD model are based on the assumption that the gas generation takes up to 13 years to take place. Although it appears that the FOD model shows lower emission than the DM model, what is not taken into account in this analysis is the emissions that will occur as a result of previous waste deposition as this has not been calculated here. This should be taken into account in the following analyses.

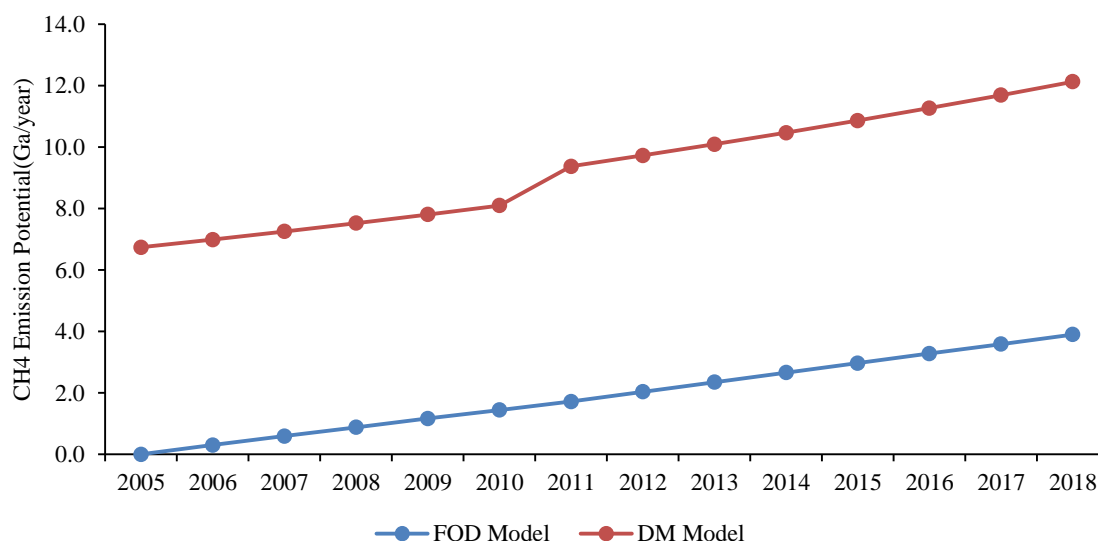


Figure 9: CH₄ emissions in Sisdoile landfill site using various Models

Using the FOD base NV Afvalzorg model alongside the DM model for historic and projected CH₄ emissions and the annual 2005-2018 waste disposal quantity (tonnes/year) current and future methane emissions were estimated for each scenario, these are shown in Figure 10, where scenario S0 and S1 overlaps since same volume of waste are disposed in landfill under these scenario. It is also assumed that the degradation takes place in two stage. The first stage starts after 1 year of MSW deposition and rate increases, which continue for 10 years. Therefore, there is no CH₄ creation in the primary year of 2005, when landfilled was started.

The NV Afvalzorg model simulations demonstrate that ‘quickly and moderately biodegradable’ organic wastes starts decaying after a year after being placed in the landfill. Production of CH₄ occurs from 2006 at an increasing rate for each scenario, peaking in 2018 after 13 years. Emissions peak at 3,897 (mg/year) for S0; 2,672 mg/year for S2; 3,565(mg/year) for S3; and 2,346(mg/year) for S4, followed by a decrease throughout the following 20 years. The ‘gradually biodegradable’ portions start disintegrating around 5 years after burial peaking by 2018, 10 years subsequent to landfilling. Over the initial 30 years, roughly 80% of all CH₄ will be created. Emission continue until 2100. Accordingly, the life expectancy of the landfill site is around 100 years and the most reasonable time to capture CH₄ is from 2006 to 2035.

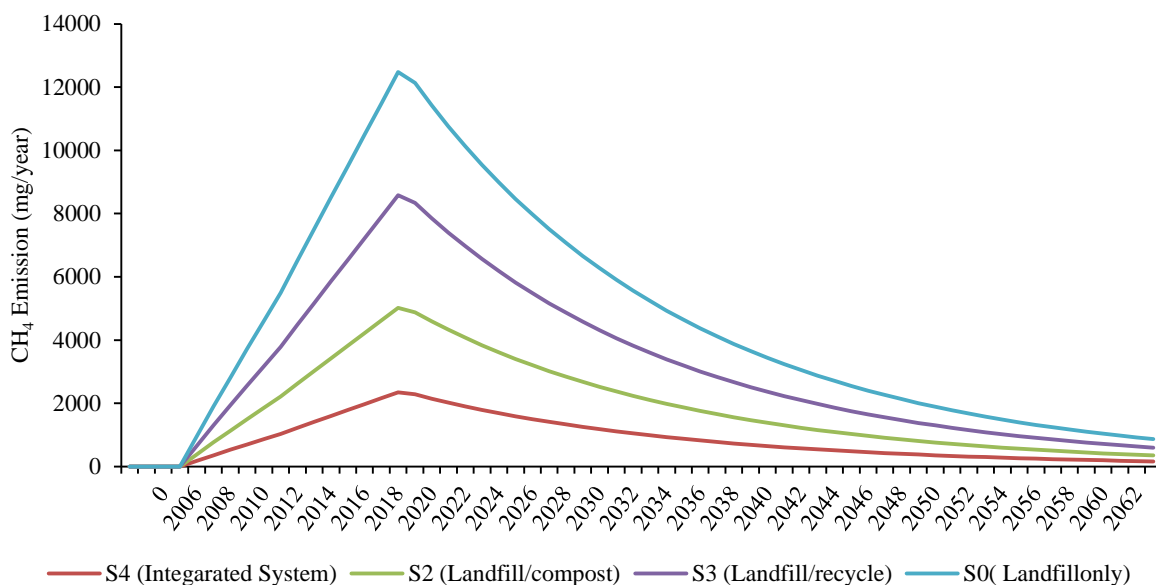


Figure 10: Methane emissions in Sisdoile landfill site over time for scenarios

IV. CONCLUSION

This research was carried out to determine the Kathmandu Metropolitan City (KMC) solid waste management system which has the potential to achieve the greatest reduction in methane (CH₄) emissions based on the five suggested scenarios developed for the study: S0, S1, S2, S3, and S4, where S0 is Business as usual and other are alternative scenarios tested to reduce CH₄ emission. The scenarios were tested using the Life Cycle Assessment (LCA) tool alongside the default and first order decay methods as suggested by Intergovernmental Panel on Climate Change (IPCC), and methane emissions under different scenarios were compared.

The results showed that CH₄ emissions are extremely high at 15,136 thousand m³ for scenario S0 - "Business as usual". A significant reduction of 53% of CH₄ emissions is achieved with gas capture (S1). Composting (S2) achieves a reduction of 35% reflecting the high organic content of waste that is currently landfilled. Recycling (S3) only achieves a reduction of 10%. Unsurprisingly, the greatest reduction in CH₄ emissions occurs with a combination of gas capture, composting and recycling (S4) with a 73% reduction.

The NV Afvalzorg model simulations demonstrate that production of CH₄ starts from 2006 i.e. after one year from landfill being placed in 2005 at an increasing rate for each scenario, peaking in 2018 after 13 years. The measure of CH₄ outflows determined by the NV Afvalzorg FOD model is far lower than the IPCC default model because only decomposable materials which produce CH₄ (organic waste, paper, textile, rubber and leather) are considered in the latter model.

The average total volume of Municipal Solid Waste (MSW) generated in KMC between 2005 and 2018 was approximately 516 tonnes/day. This has been projected to increase by 9.6% per year creating many challenges in the management of solid waste in KMC. The unit rate of waste generation in KMC is 0.3 kg/person/day, with organic waste being the highest percentage (63%) in total waste.

Given the current composition of waste that is deposited at Sisdoile landfill site, it is suggested that the feasibility of gas capture and composting is investigated as alternatives. Recycling material should also be considered long term as plastics and similar may in the future take up a greater proportion of the waste material over time.

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